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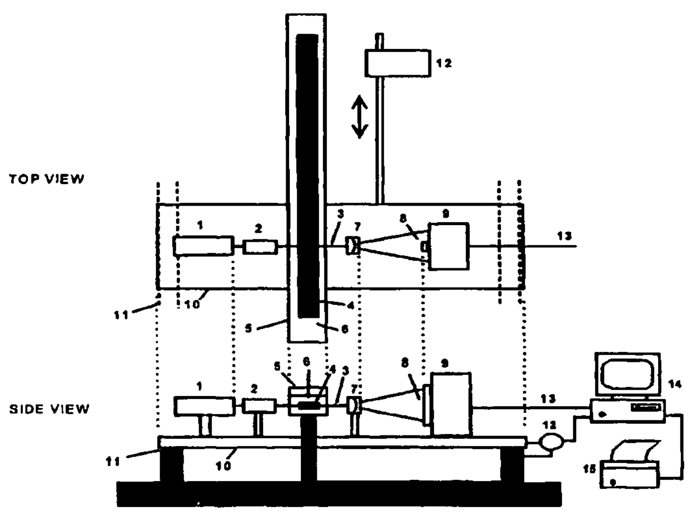
(54) Title: METHOD AND APPARATUS FOR IMAGING INHOMOGENEITY IN A TRANSPARENT SOLID MEDIUM



(57) Abstract: This invention is related with a method and apparatus for inspecting chemical inhomogeneities in a solid transparent material by way of generating a shadow image of the sample material and recorging said image digitally or photographically. The method consists of scanning the shadow image of a stationary sample where the illuminance information across the sample thickness is combined with position information along the sample in order to generate a shadow image of the sample. The method and apparatus signaficantly reduce analysis time, material and energy costs, and increase image quality and test safety especially in the case of analysis of inhomogeneities in samples of glass manufacture such as float glass.

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METHOD AND APPARATUS FOR IMAGING INHOMOGENEITY IN A TRANSPARENT SOLID MEDIUM

FIELD OF THE INVENTION

This invention relates to methods for imaging inhomogeneities in the index of refraction of a solid transparent medium using the shadow or Schlieren optical systems, and an apparatus which generates photographic or digital images of such transparent media by way of scanning said image. The apparatus is especially useful in inspection of glasses for internal chemical inhomogeneity.

BACKGROUND OF THE INVENTION

Internal structure of commercial glass articles, such as flat glass, containers, tableware or optical glasses, may contain chemical inhomogeneity, which is a variation of chemical composition and light refractive index, which manifests itself as optical aberrations in the glass article. These inhomogeneities may arise from inadequate mixing of the ingredients of the glass in the melting tank and may be arrested in the glass article during the formation of the article. The detection of these optical aberrations is of major concern for glass manufactures.

Float glass is manufactured by spreading and solidifying molten glass on a bath of molten tin and subsequent heat treatment of the glass. Chemical inhomogeneities in the structure of molten glass are arrested in the internal structure of the solidified glass as numerous layers of glass with slightly different chemical and optical properties. Qualitative and quantitative examination of these two-dimensional inhomogeneities gives useful information to the manufactures regarding the melting conditions in the glass tank prior to forming. Therefore, it is vital for glass manufacturers to obtain high-quality cross-sectional images of float glass at certain times during manufacture of the glass. Similarly, inhomogeneities in other glass articles such as glass containers, tableware and optical

glasses, need to be inspected for optical, mechanical and thermal quality.

Chemical inhomogeneities in the internal structure of a solid transparent medium can be viewed by shadow or Schlieren optical systems (SPSE Handbook of Photographic Science and Eng., Ed.W.Thomas,Jr., John Wiley&Sons, 1973.) In both systems, a perfectly parallel and uniform beam of light is allowed to pass through the said transparent medium. In the shadow system, the shadow of the transparent object is thrown on a screen or a photographic material. If the incident beam is of uniform intensity, the inhomogeneities of the medium observed on the screen or photographic material are approximately proportional to the second derivative of the light refractive index with respect to distance. The refraction of the rays of incident light results in some distortion of the projected image so that the image does not correspond exactly to the object. In the case of a narrow strip of float glass sample illuminated by a uniform and parallel beam of light incident perpendicular to the cross-sectional surface of the sample and parallel to the internal layers of chemical inhomogeneity, the shadow image thrown on a screen is composed of numerous lines of varying illumination.

In the Schlieren system, the image of the transparent medium is focused on a screen by way of a lens system. The basic system uses a simple knife-edge as the spatial filter so that the illumination in the image depends on the extent to which the light beams from the object pass over or are blocked by the knife edge.

Shadow system is more stable, due to lack of a knife-edge, easily and cheaply constructed and its image consists of finer details when compared with the Schlieren system. The requirement to use a small light source with the shadow system can be overcome by using a laser light source which provides parallel and uniform illumination for shadow system.

General principles for refraction of light in continuous refractive index gradients are as follows :

- The ray is always deflected toward regions of higher refractive index.
- The deflection is proportional to the path length and the rate of change of refractive index with distance orthogonal to the ray.
- Components of the refractive index along the ray do not produce a deflection.

If a shadow or Schlieren optical system is used for obtaining images of chemical inhomogeneity in a solid transparent object, the optical effects of the interaction of the incident light rays with the surfaces of the object orthogonal to the incident light rays need to be eliminated from the resultant image of the object. For this reason, either the object must be submerged in a liquid having a light refractive index approximate to that of the object, or the surfaces of the object orthogonal to incident light rays must be ground flat and polished.

Similar to chemical inhomogeneities in transparent objects observed under substantially uniform temperature, thermal inhomogeneities generated in transparent objects can also be observed by shadow or Schlieren systems as a result of the effect of local temperature changes on the local light refractive index of the transparent material.

Investigation of the patent literature reveals several methods and apparatuses invented for the purpose of detecting inhomogeneities in solids such as glass by optical methods. Some of these methods (JP2138853 and US5752519) are not imaging methods and comprise methods of measurement of light intensity after travel through the object of investigation. Inspecting method described in JP53120587 comprises a method for the formation of an image of the inhomogeneities in a glass block to be investigated visually, but does not include a scanning method for the reproduction of the shadow image for further analysis. The method described in US5016099 is related to the inhomogeneities in float glass as viewed orthogonal to the float glass surfaces, hence is not related to cross-sectional inhomogeneity. The present invention is related to forming and recording a shadow image of chemical inhomogeneities in transparent solids such as glass, by a photographic or digital scanning technique, for the purpose of qualitatively assessing the

homogeneity of the said solid.

The analysis of the literature therefore shows that this invention is functionally different than the other inventions published.

In the flat glass industry, several attempts have been made for viewing the chemical inhomogeneities in float glass structure. The devices generally used in the glass industry are called striagraphs which utilize the shadow system in combination with a photographic recording system which is principally similar to the system described in this invention. The sample is placed perpendicular to the optical axis consisting of a light source, a projection lens and the photographic recording system, and is drawn at uniform speed across the optical axis while the image projected by the lens is recorded by the photographic recording system. The photographic system comprises a drum, around which a strip of photographic paper is wrapped, and a vertical slit which allows a narrow section of the moving image of the sample fall on a corresponding narrow section on the photographic paper while the drum rotates at in such a way that the photographic paper moves at a slower velocity than the moving image. The resulting recorded latent image of the sample is therefore compressed in the direction of image movement and enlarged in the direction perpendicular to image movement.

One major disadvantage of the traditional striagraph system is that the vibration of the sample during its travel across the optical axis causes the final recorded image to blur, rendering the analysis of chemical inhomogeneity difficult. The present invention prevents vibration of the sample by holding the sample stationary and moving the whole optical system across the sample while recording the shadow image of the sample. Furthermore, the invention makes digital recording of the shadow image possible, thus eliminating lengthy steps of photographic processing of the exposed material. Digital images can be modified for obtaining additional information such as de-spotting, negative image, unproportional resizing, pasting to one another, flipping, etc. These improvements of the invention substantially increase the image quality, and substantially

reduce image processing time and amount of materials to be used for the analysis. In the case of float glass inspection this method does not use harmful UV light for illumination, is more energy efficient, and occupies less space than the conventional system. Therefore the method and apparatus described herein substantially reduce the overall cost of qualitative analysis of inhomogeneity in solid transparent objects of manufacture and substantially increase the quality of images obtained for analysis.

The analysis of the industry practice therefore shows that this invention is functionally different than the traditional practice.

DETAILED DESCRIPTION OF THE INVENTION

This invention is related to methods of imaging and analyzing chemical inhomogeneities in solid transparent materials and various forms of an apparatus which utilize these methods. It is an object of the invention to develop a method and a device for the fast, efficient, safe and high-quality representation of the chemical and thermal inhomogeneities in transparent objects, such as glass, plastics or ceramics, for the purpose of analyzing and controlling manufacturing conditions of these objects. It was surprisingly discovered that efficient, safe and high-quality recording of the spatial distribution of inhomogeneities in a transparent object, such as the relative positions of inhomogeneous layers along the entire width of a float glass ribbon, could be achieved through digitally or photographically scanning the shadow or Schlieren image of that object while the object was held stationary.

The method consists of;

1- A sample of transparent solid material whose surfaces orthogonal to the optical axis of the system are either polished or immersed in a liquid having a light refractive index approximate to that of the sample,

2- A light source radiating a uniform and parallel beam of light for the illumination of the sample, such as a laser light source or a collimated beam of light from a halogen light source, where the diameter of the beam of light is larger than the area to be examined in the sample,

3- A mechanical system which moves the optical and recording systems at fairly uniform speed with respect to the stationary sample,

4- A digital recording system which processes position information from the movement of the optical system via an encoder in combination with illuminance information from the shadow of the sample thrown by the optical system on an optical sensor, for the construction of a two-dimensional representation of the chemical inhomogeneities in the sample. As an alternative to the digital recording system, a photographic recording system can be employed, which comprises a narrow slit positioned between the sample and a strip of photographic film or paper, and a mechanism which allows the strip of the photographic paper to be moved in the direction of movement of the projected image of the sample at a speed proportional to the speed of the optical system relative to the stationary sample.

Figure 1 represents the best form of application of the invention, in which a digital system is utilized for imaging the inhomoheneities in the sample.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 describes the apparatus which records the shadow image of the sample digitally. Light source 1 generates a beam of laser or halogen light 3, expanded by beam expander 2 which illuminates sample 4 immersed in liquid 6 of approximate light refractive index to that of the sample in sample container 5 constructed with substantially optically clear sheet material and placed in such a way that two opposite surfaces of the sample container are approximately orthogonal to the direction of incident laser beam.

Light beam emerging from the sample container is projected by optical lens 7 onto light sensor 8 of scanner 9 connected to computer 14 by connection 13. The position and focal length of optical element 7 along the optical axis between sample 4 and sensor 8 determines size of the projected image of the sample on sensor 8. Encoder 12 generates a position signal from motion of plate 10. Lighting and optical elements 1, 2, and 7, and scanner 9 are placed on plate 10, which can be moved on bearing 11 by mechanical actuator 12 at a fairly uniform speed relative to the stationary sample 4 and sample container 5. Computer 14 is used to capture, record and process the image generated by scanner 9. Final processed image can be printed on printer 15.

Figure 2 describes the apparatus which records the shadow image of the sample photographically. Light source 1 generates a beam of laser or halogen light 3, expanded by beam expander 2 which illuminates sample 4 immersed in liquid 6 of approximate light refractive index to that of the sample in sample container 5 constructed with substantially optically clear sheet material and placed placed in such a way that two opposite surfaces of the sample container are approximately orthogonal to the direction of incident laser beam. Light beam emerging from the sample container is projected by optical lens 7 onto slit 8 of specified width placed vertically on light-tight box 9. Drum 10 with a vertical axis of rotation is placed inside box 9. Slit 8 is of sufficient length so that projected image of the sample entirely illuminated photographic sheet 13, in the form of film or enlarging paper, wrapped around drum 10. Lighting and optical elements 1, 2, and 7, box 9 and gear mechanism 14 are placed on plate 10, which could be moved on bearing 11 by mechanical actuator 12 at a fairly uniform speed relative to the stationary sample 4 and sample container 5. Mechanism 14 is linked to drum 10 and allowed the drum to be rotated at an angular speed proportional to the speed of Plate 10 during movement of the plate, so that the linear speed of photographic sheet 13 was less than the speed of Plate 10. Mechanism 14 is made up of gears that rotate drum 10 in such a way that shadow image of the sample projected onto slit 8 moves in the same direction as the portion of sheet 13 illuminated by the slit. The position and focal length of optical element 7 along the optical axis between sample 4 and slit 8 determines size of the

projected image of the sample on slit 8. The width of slit 8 can be adjusted between 0.1 and 3 mm for the purpose of adjusting exposure and image sharpness on sheet 13.

EXAMPLES

The following Examples are provided to illustrate how the method of this invention was applied to various apparatuses. Examples are in no way inclusive of the possible combinations of mechanical, optical, photographic or digital systems or samples which can be employed to apply this invention.

Example 1

An apparatus was constructed as shown in Figure 1. Samples were clear and colored float glass strips of 115 mm length, 2 – 19 mm thickness and 1.5 – 4 cm width. The samples were placed in the sample container bath filled with dimethylphythalate or silicone oils or almond oil that have light refractive indices close to that of float glass. A hand-held scanner hardware was rearranged so that the scanner card mounted in the computer would capture a scanned image of the sample by using light intensity reading from the sensor directly exposed to the shadow image projected by the optical lens of either converging or diverging type, and the position information from an encoder installed on the plate. The image obtained surprisingly showed in detail the layers of minute chemical inhomogeneity in the float glass samples when compared with the traditional photographic system in which the sample glass was carried across the optical axis of a shadow system. Since inspection of crossection of an entire 3.5 m width of float glass ribbon necessitates a compaction of the crossection image along its longer dimension and enlarging in its shorter dimension (along glass thickness), the scanning procedure was equipped with a facility to perform compaction and enlarging functions. The enlarging was done by the magnification of the optical lens and the compaction function was performed by adjusting the encoder and also by way of an image processing software installed in the computer. The scanning was completed in 20 – 60 s depending on the speed of the plate that could be controlled manually. The whole apparatus occupied much less space than the traditional striagraph system and the

whole procedure was significantly faster, more efficient, cheaper and user friendly. High quality striagrams, that is, images of chemical inhomogeneity, of float glass were obtained. The apparatus was successfully utilized for inspection of float glass for defects such as ream and optical defects, as well as for investigating the effects of changes in certain glass melting parameters, such as effect of mixers, bubblers, batch chargers, coolers or tweel, on the formation of chemical inhomogeneity structure within the glass.

Example 2

The same apparatus described in Example 1, except the light source was a halogen light source emitting a substantially uniform and parallel beam of light. High quality striagrams of float glass were obtained.

Example 3

The same apparatus described in Example 1, except sample length was 10 cm and sample was not immersed in a liquid of approximate light refractive index, but the surfaces of said sample orthogonal to the incident light were ground flat and polished so that light from said source was not substantially scattered by said surfaces upon entering and leaving the sample. High quality striagrams of float glass were obtained.

Example 4

The same apparatus described in Example 1, except the shadow image of the sample was projected, as shown in Figure 2, through a vertical narrow slit onto a photographic material which moved at a speed smaller than, proportional to, and in the same direction as the speed of the shadow image across the slit. For this purpose, a sheet of photographic film or paper was wrapped around a drum positioned in a light-tight box that contained the slit as was the case in the traditionally used striagraph set-up. The drum was rotated about an axis parallel to the slit by way of a gear system, while the photographic material was exposed by the light passing through the slit. The system was different from the traditional system because the sample was held stationary. The new apparatus produced much sharper images than traditional striagrams.

CLAIMS

1. A method by which an image of a solid transparent object is generated and recorded by way of scanning a projected shadow of said object wherein inhomogeneities in the structure of said object can be seen.
2. An apparatus that utilizes the principles of the method described in Claim 1 where the apparatus comprises a light source capable of emitting a uniform and parallel beam of light for the illumination of sample, an optical element of converging or diverging type for projecting an image of the sample, and a light recording device, which are all positioned along a common opticle axis and mounted on a plate that can be moved relative to a stationary solid transparent sample positioned between the light source and the opticle element.
3. The same apparatus described in Claim 2 where the light recording device is a digital scanner which generates a scanned image of the shadow image of the sample by utilizing the position information from the motion of the plate.
4. The same apparatus described in Claim 2 where the light recording device is a mechanical photographic scanner which records a latent image of the shadow image of the sample utilizing a narrow opening for projecting a specific section of the shadow image on a corresponding specific point of the photographic material.
5. The same apparatus described in Claim 2 where the light source is positioned stationary with respect to the sample in such a way that light beam is parallel to the direction of motion of the plate and light beam is reflected to the sample by a mirror positioned on the plate at an angle of 45° to light beam.
6. The same method described in Claim 1 where the sample is immersed in a liquid of approximate light refractive index to that of sample, in a container with transparent walls that are placed approximately orthogonal to the incident illumination from light source.
7. The same method described in Claim 1 where the surfaces of the sample orthogonal to incident illumination are ground flat an polished to prevent scattering of the incident light upon entering or leaving the sample.

8. The same method described in Claim 1 where the surfaces of the sample orthogonal to incident illumination are in contact with a flat piece of transparent material and a liquid of approximate light refractive index to that of sample is held by capillarity between the said flat transparent material and the sample surfaces.
9. The same apparatus described in Claim 2 where the sample is a piece of glass.
10. The same apparatus described in Claim 2 where the sample is a strip of float glass with dimensions of length 1 cm - 400 cm, width 0.5 cm - 10 cm and thickness 0.2 mm to 20 mm.
11. The same apparatus described in Claim 10 where the sample is placed across the optical axis of the apparatus in such a way that the cross-sectional surfaces of the sample are orthogonal to the incident illumination from the light source for the purpose of inspecting layers of chemical inhomogeneity within the glass structure.
12. The same apparatus described in Claim 2 where the aspect ratio of the recorded image of the sample is 10^{-4} to 100 times the aspect ratio of the sample.

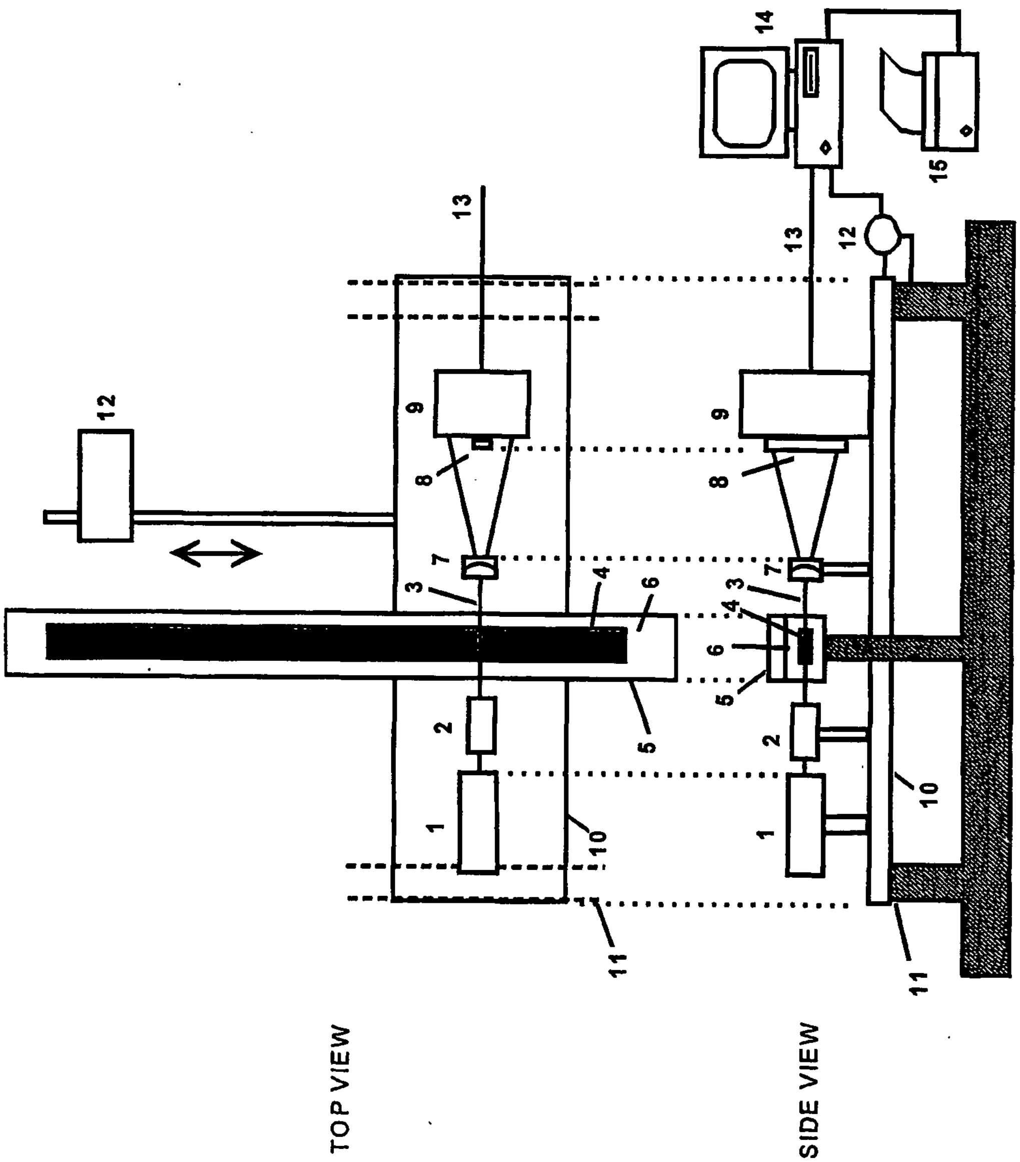

FIGURE 1

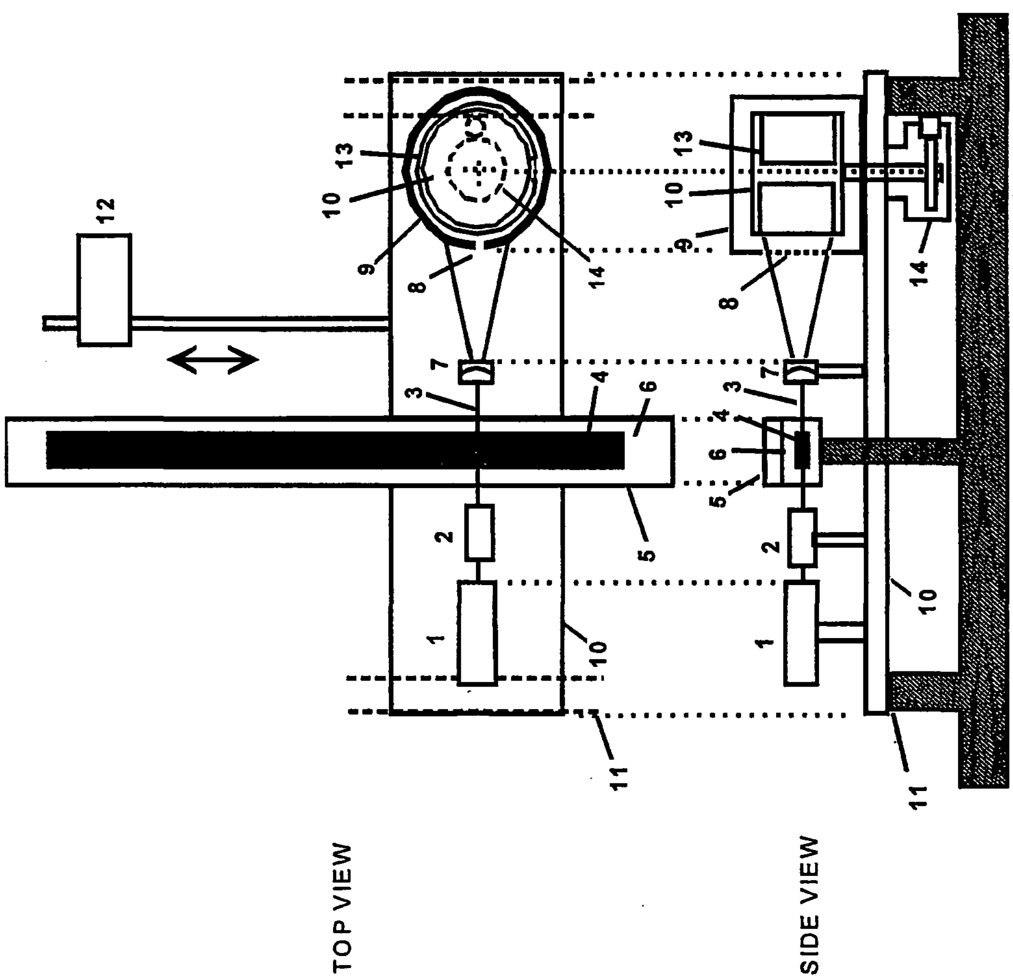

FIGURE 2

INTERNATIONAL SEARCH REPORT

International application No.
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CLASSIFICATION OF SUBJECT MATTER

IPC^7: G01N 21/89, 21/896, 33/38

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC^7: G01N 21/89, 21/896, 33/38

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X	US 5016099 A (W. BONGARDT) 14 May 1991 (14.05.91) abstract, claims, figs. 1,2.	1,9
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X	EP 0559433 A1 (NIPPON SHEET GLASS) 8 September 1993 (08.09.93)	1,3,9
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☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
„A" document defining the general state of the art which is not considered to be of particular relevance
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Date of the actual completion of the international search	Date of mailing of the international search report
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Name and mailing adress of the ISA/AT Austrian Patent Office Kohlmarkt 8-10; A-1014 Vienna Facsimile No. 1/53424/535	Authorized officer ERBER Telephone No. 1/53424/410

INTERNATIONAL SEARCH REPORT

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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